Imaging Exoplanets with the WFIRST Coronagraph Instrument

Dr. Margaret A. Frerking

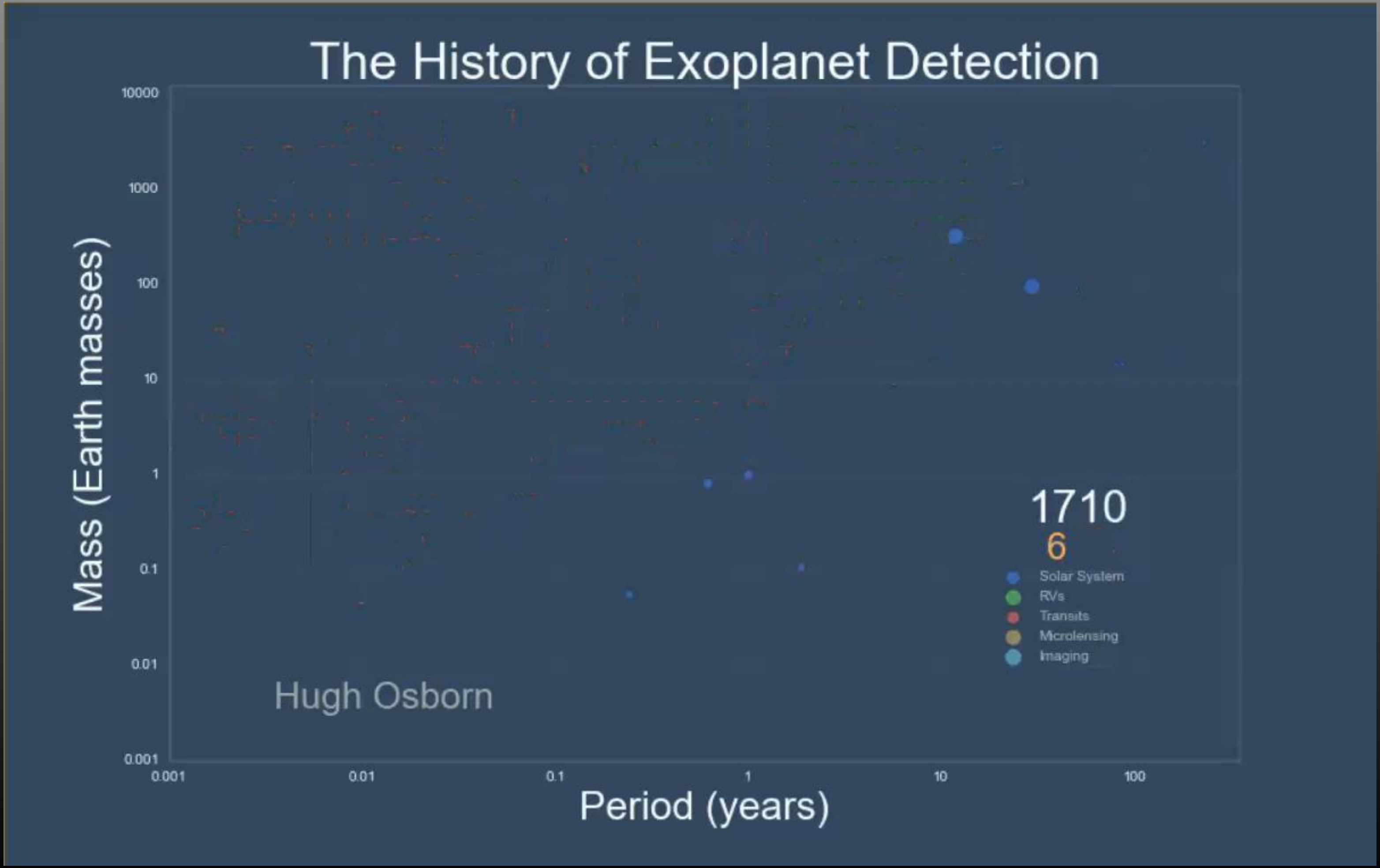
Manager, WFIRST Coronagraph Instrument

Jet Propulsion Laboratory

California Institute of Technology

Exoplanets – A major shift in understanding the Universe

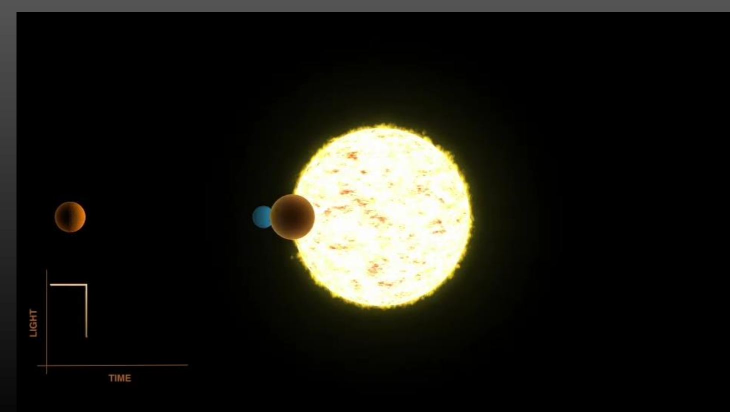
Mass vs Orbital Period



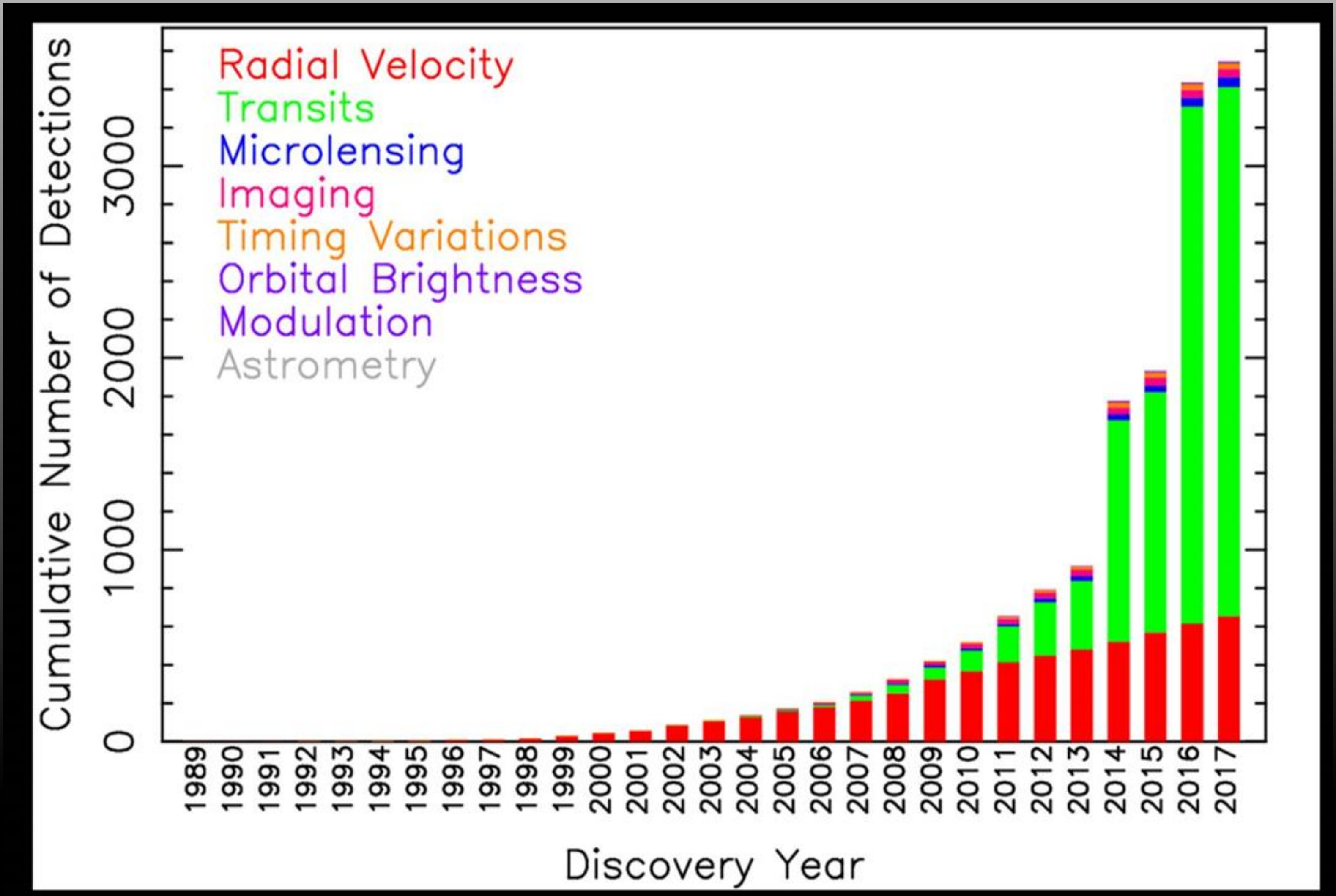
How do we find Exoplanets?

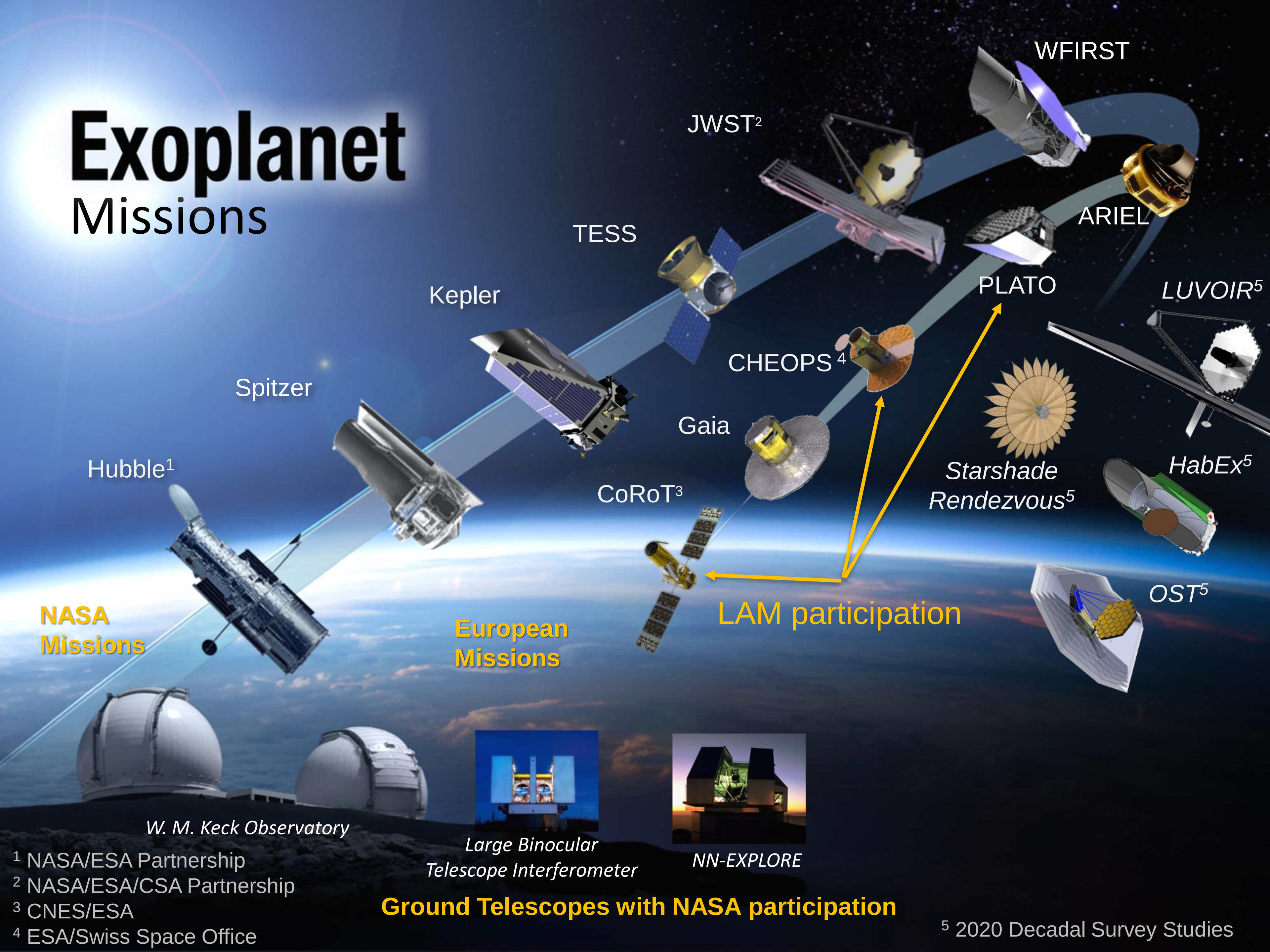
- Doppler Spectroscopy (Radial Velocity)

- Exoplanet transits



Number of Exoplanets discovered doubles every 2 years





Exoplanet
Missions
WFIRST
JWST[2]
ARIEL
TESS
PLATO
Kepler
LUVOIR[5]
CHEOPS [4]
Spitzer
Gaia
Starshade
Rendezvous[5]
Hubble[1]
HabEx[5]
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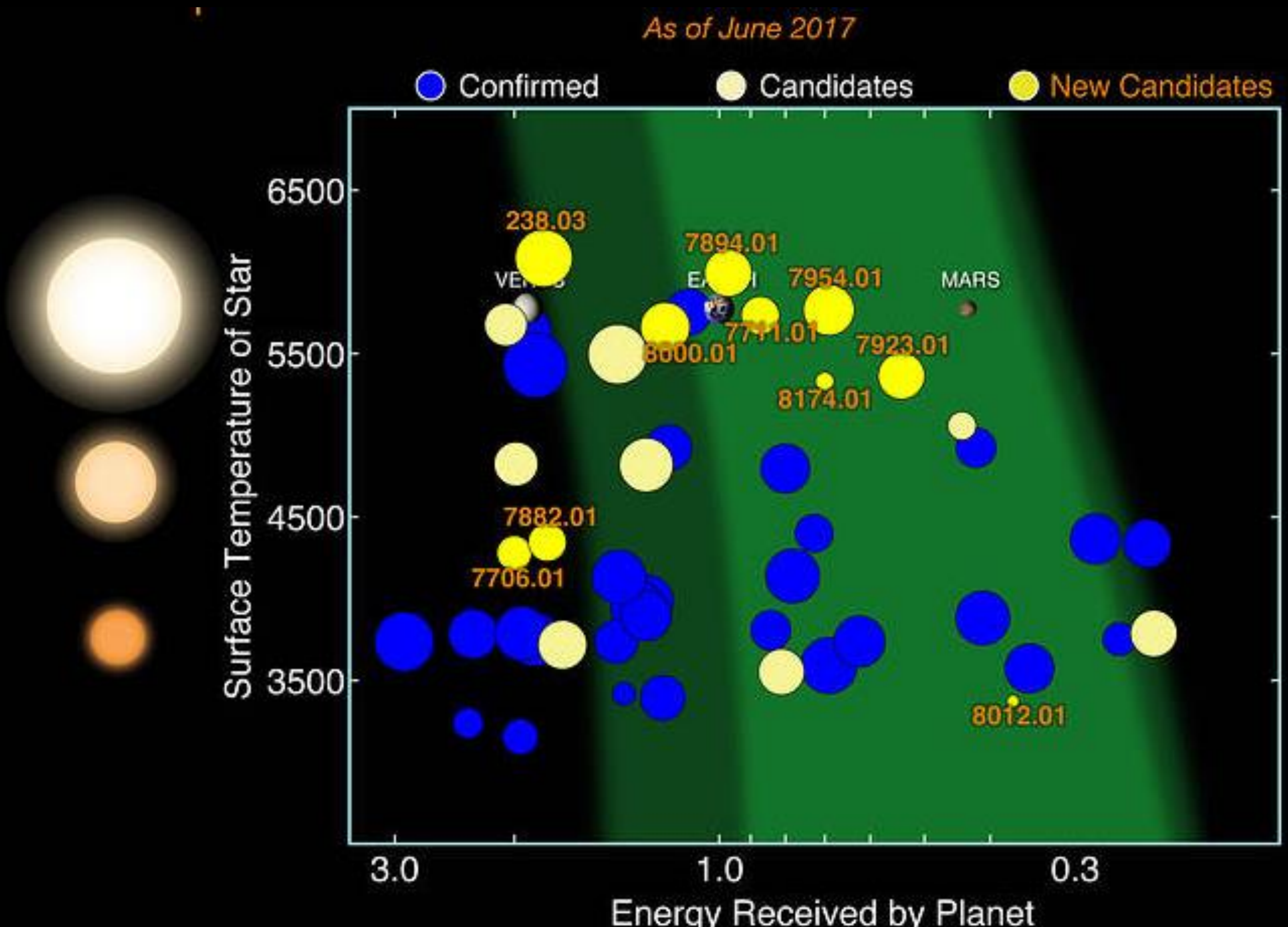
OST[5]
LAM participation
NASA
Missions
European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
Ground Telescopes with NASA participation
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office
[5] 2020 Decadal Survey Studies

Kepler Habitable Zone Planets



Recent Data Release 25 identifies additional HZ candidates and their reliability, S. Thompson et al.

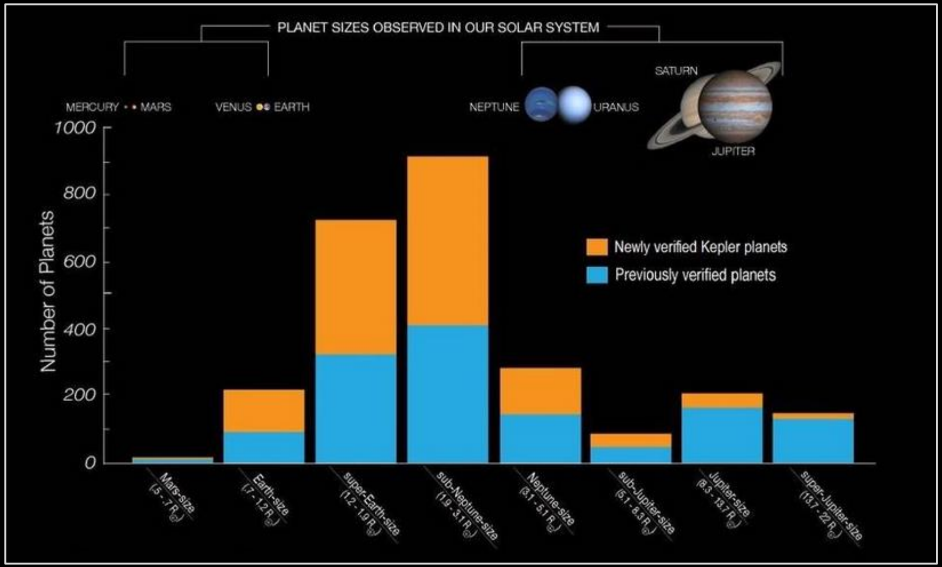
Credit: NASA/Ames Research Center/W. Stenzel

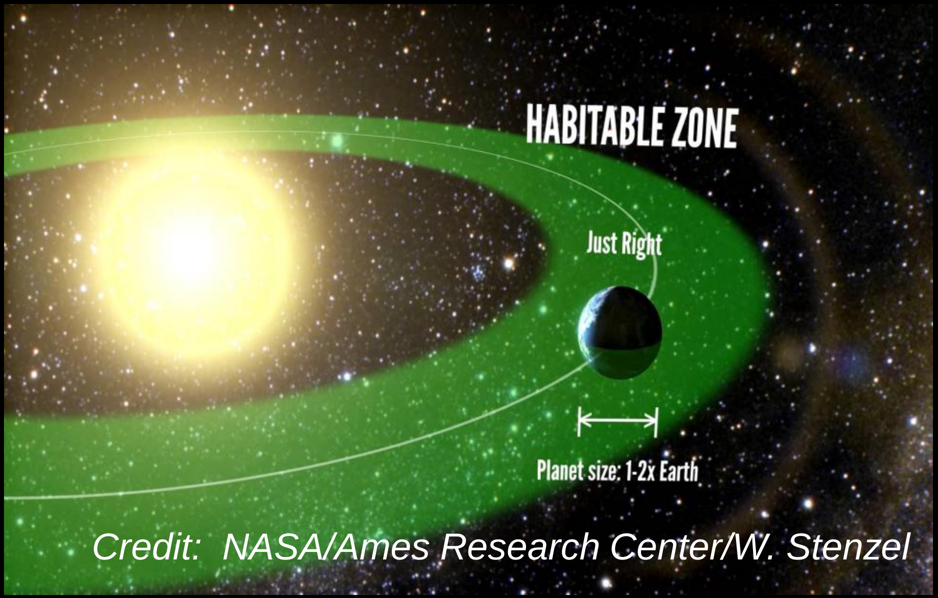
Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky

2. Small planets are the most common type in the Galaxy

3. Earth-sized planets (0.5 to ~1.5 Earth radii) in the Habitable Zone are common

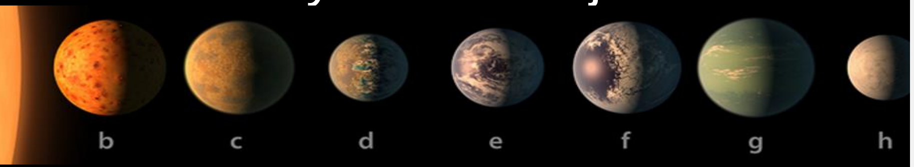




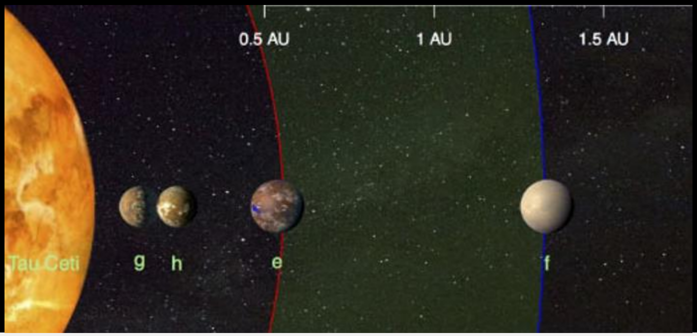
Credit: NASA/Ames Research Center/W. Stenzel

Exoplanet Science News

Courtesy: E. Mamajek

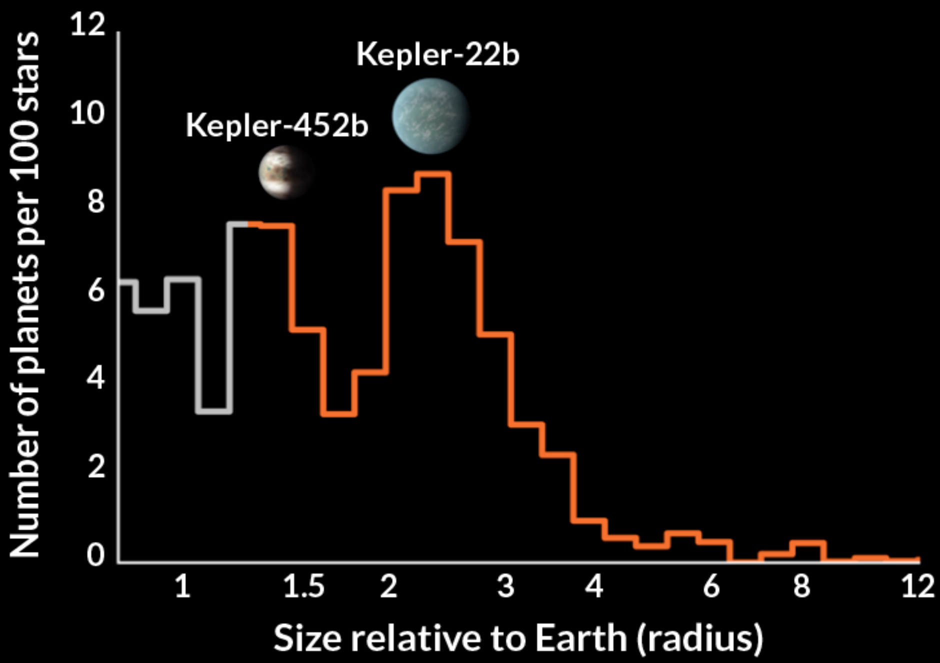


- Gillon et al. (2017, Nature) reported discovery w/Spitzer that the nearby ultra cool dwarf TRAPPIST-1 has 7 transiting Earth-sized exoplanets.



- Feng et al. 2017 found evidence for four planets in new HARPS data of the nearby star τ Ceti.

- Fulton et al. (2017) reported strong evidence for gap between “super-Earth” and “sub-Neptune” exoplanets using Kepler data + spectroscopic data for stars from Keck.

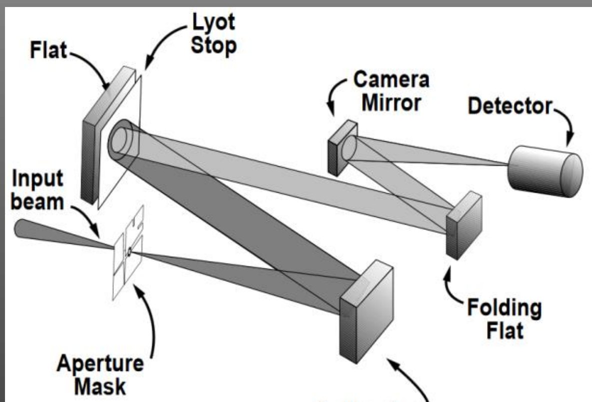


Direct Imaging with a Coronagraph

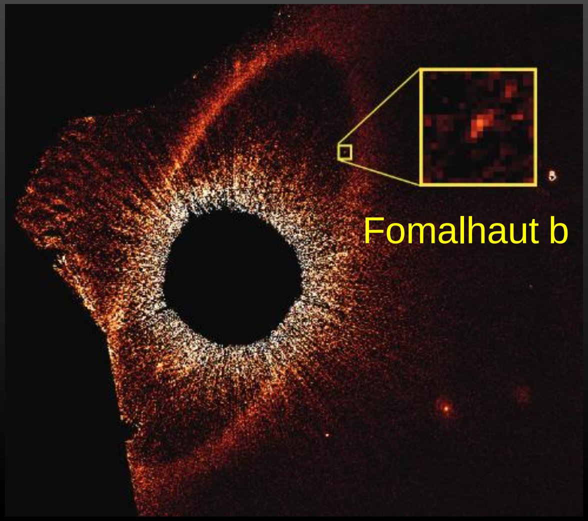
Imaging exoplanets with previous coronagraphs in space – no active optics

Hubble has had three Lyot coronagraphs used in its instruments to look at planets:

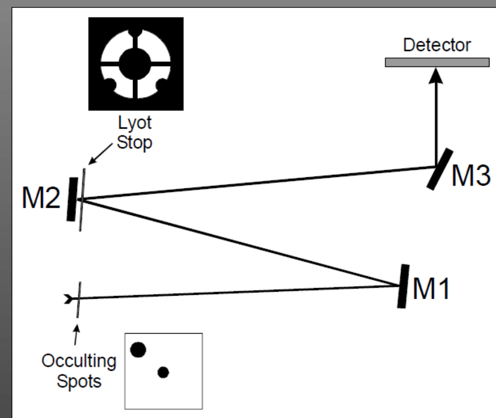
STIS



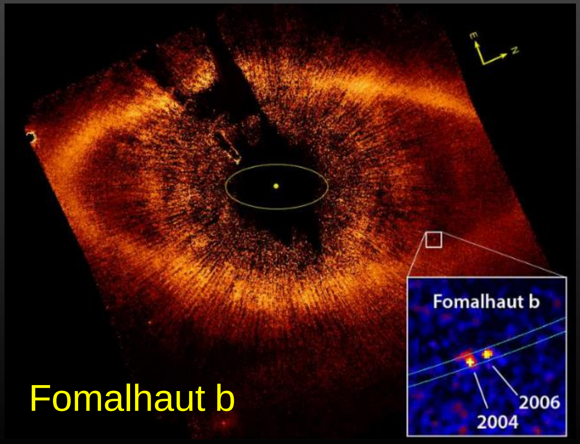
Heap *et al.* 2000



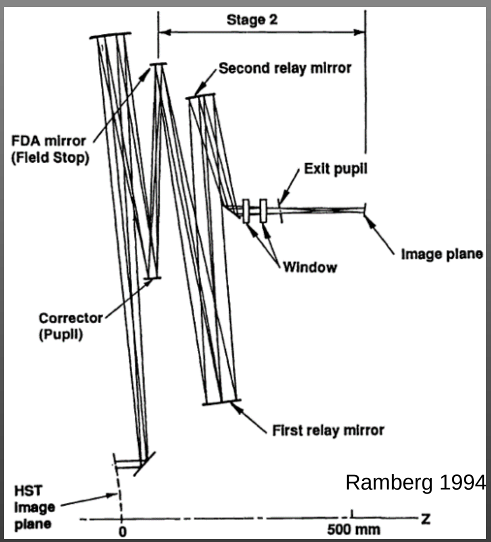
ACS/HRC



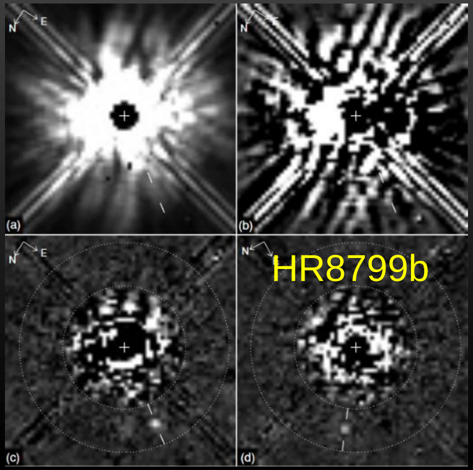
Krist *et al.* 2003



NICMOS



Ramberg 1994



WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

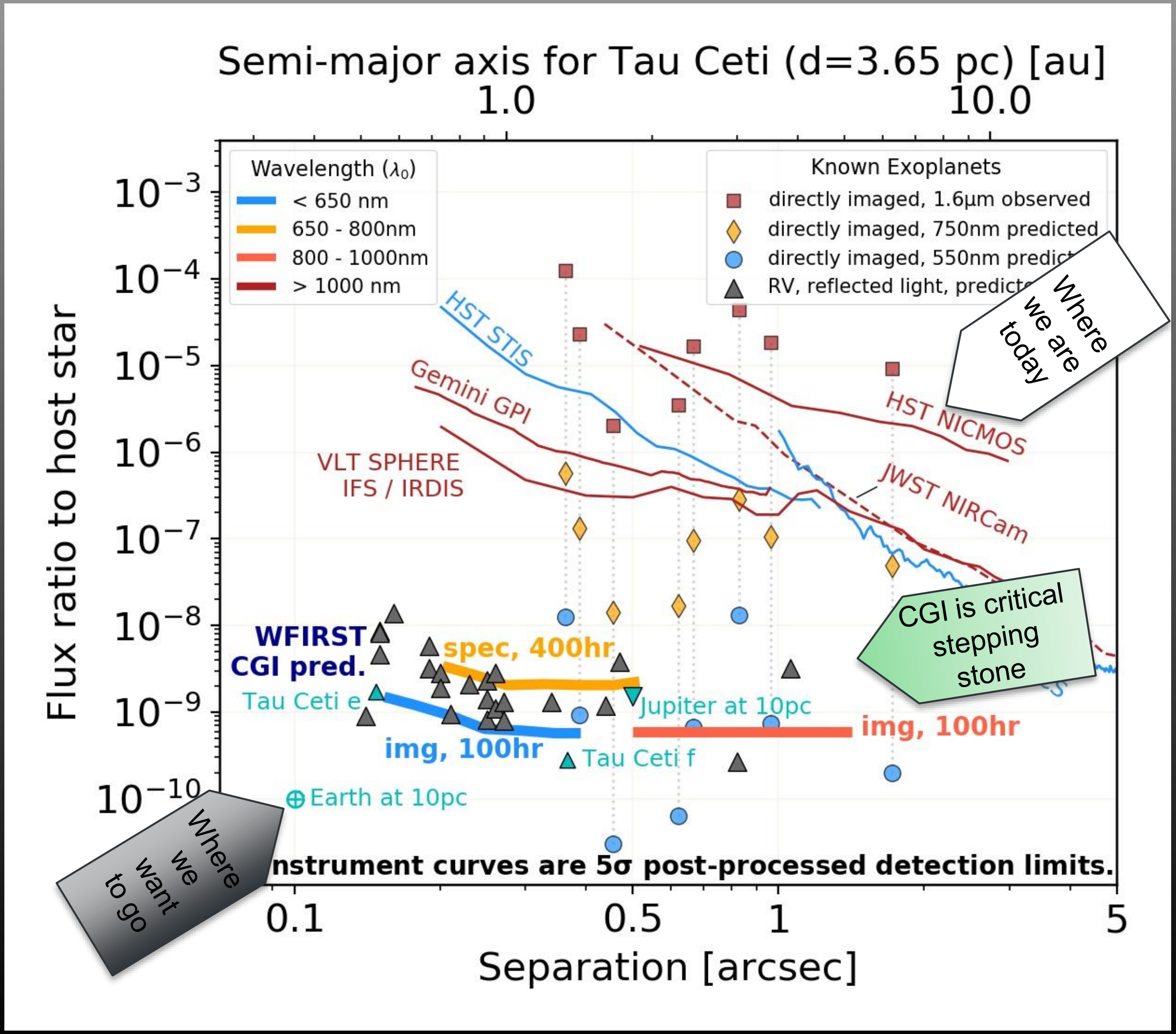
Coronagraph Instrument is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets

CGI projected performance is a 1000 fold improvement in contrast compared to space- and ground-based state-of-the-art observatories

- Enabled by active control of optical wavefront errors and pointing

Optical spectra of exoEarths at 10 pc requires a further x10 improvement in contrast and x2 in spatial resolution

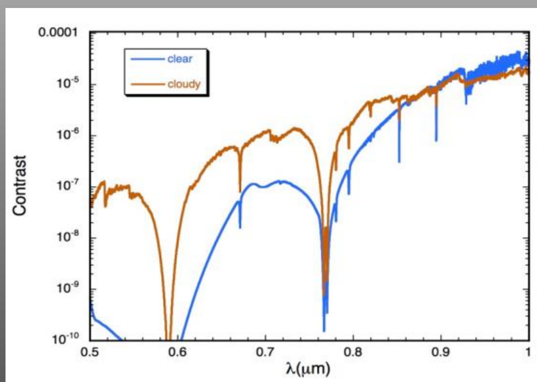
CGI is a major stepping stone that will obtain optical spectra of mature exoJupiters



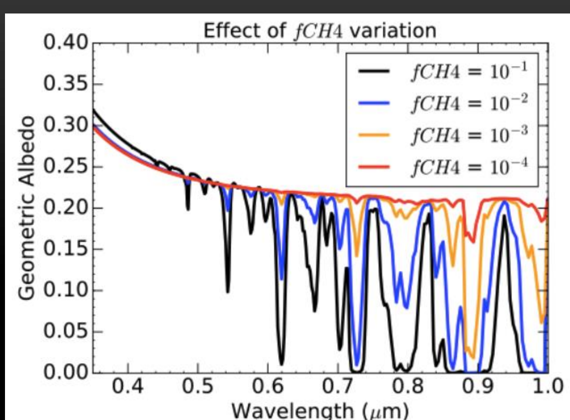
CGI Exoplanetary Science Themes

WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

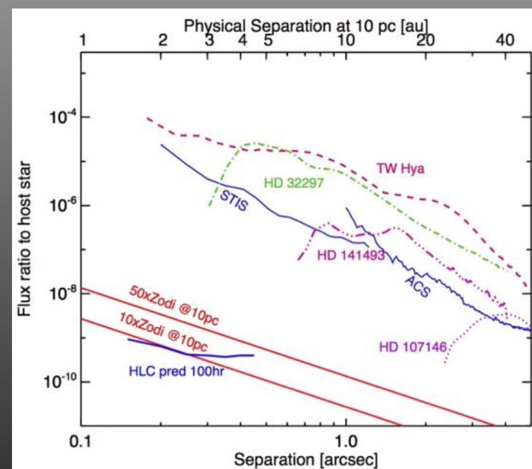
Self-luminous, young super Jupiters: atm. properties

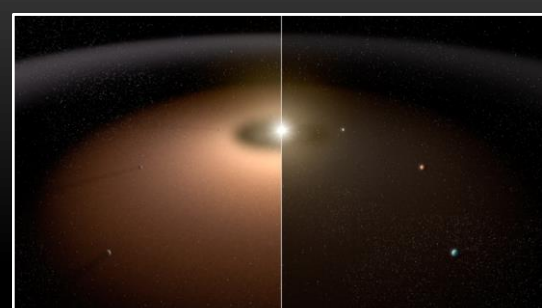


Mature Jupiter analogues in reflected light: mass & atm. properties

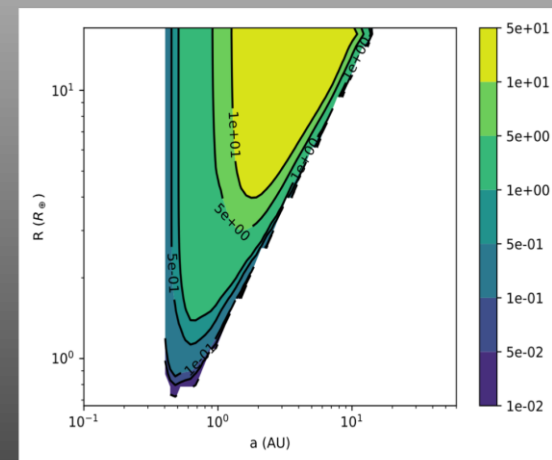


Circumstellar disks: Protoplanetary (young) Debris (mature) Exozodi (mature, HZ)





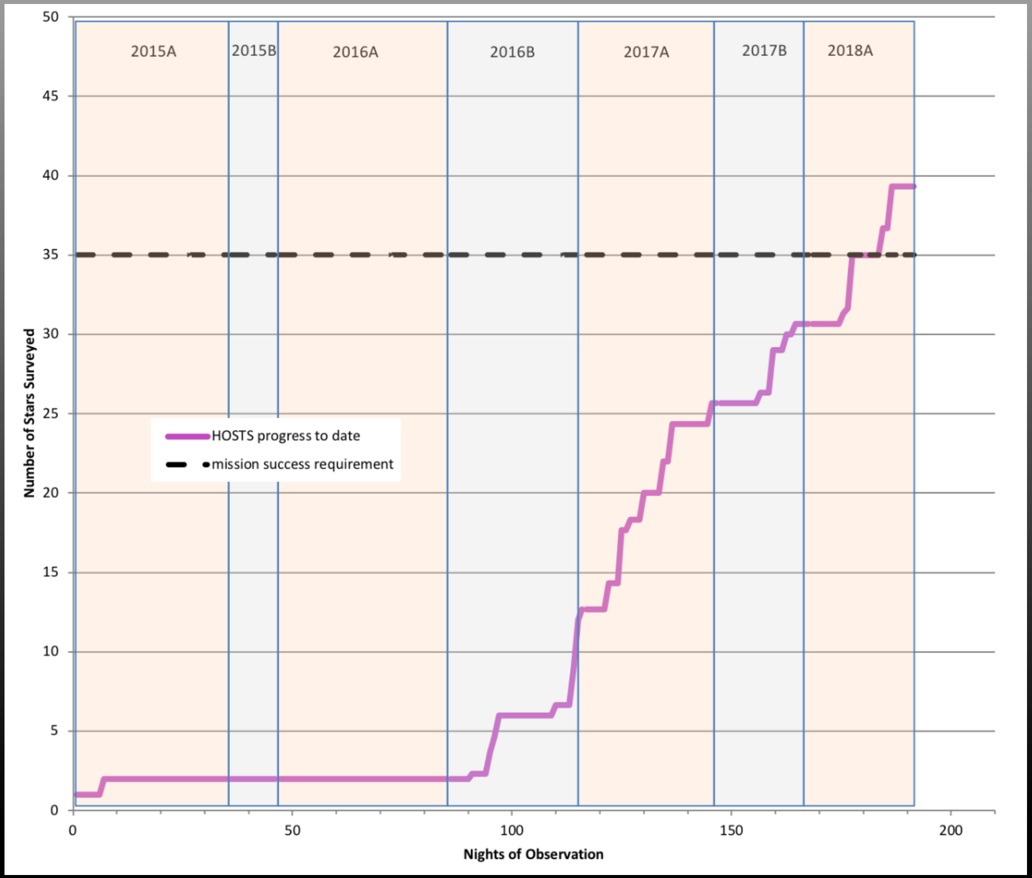
Possible blind searches for giant planets



Possible characterization of Habitable Zone of nearby systems

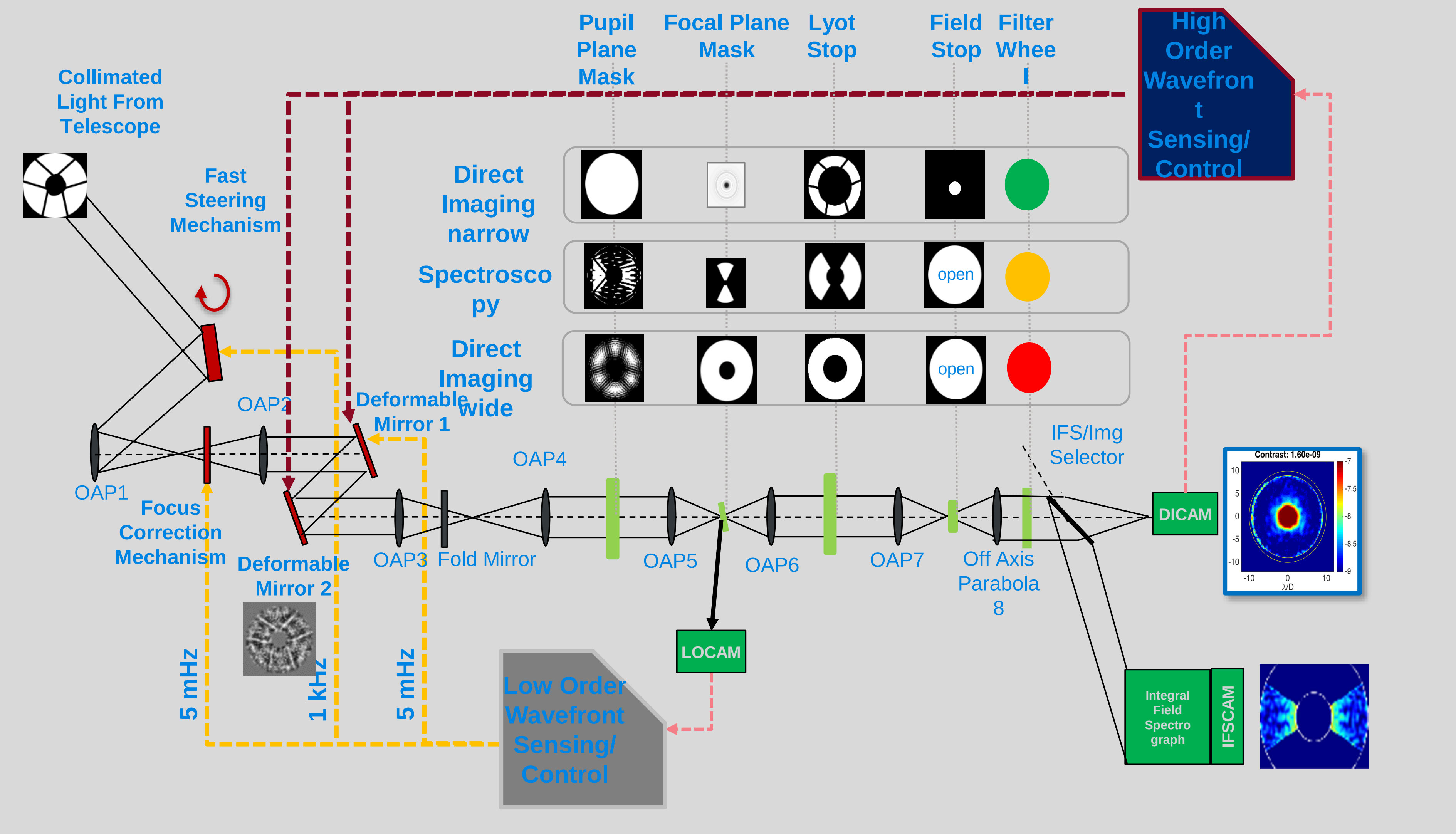
Dust around stars

Large Binocular Telescope Interferometer Stars Surveyed



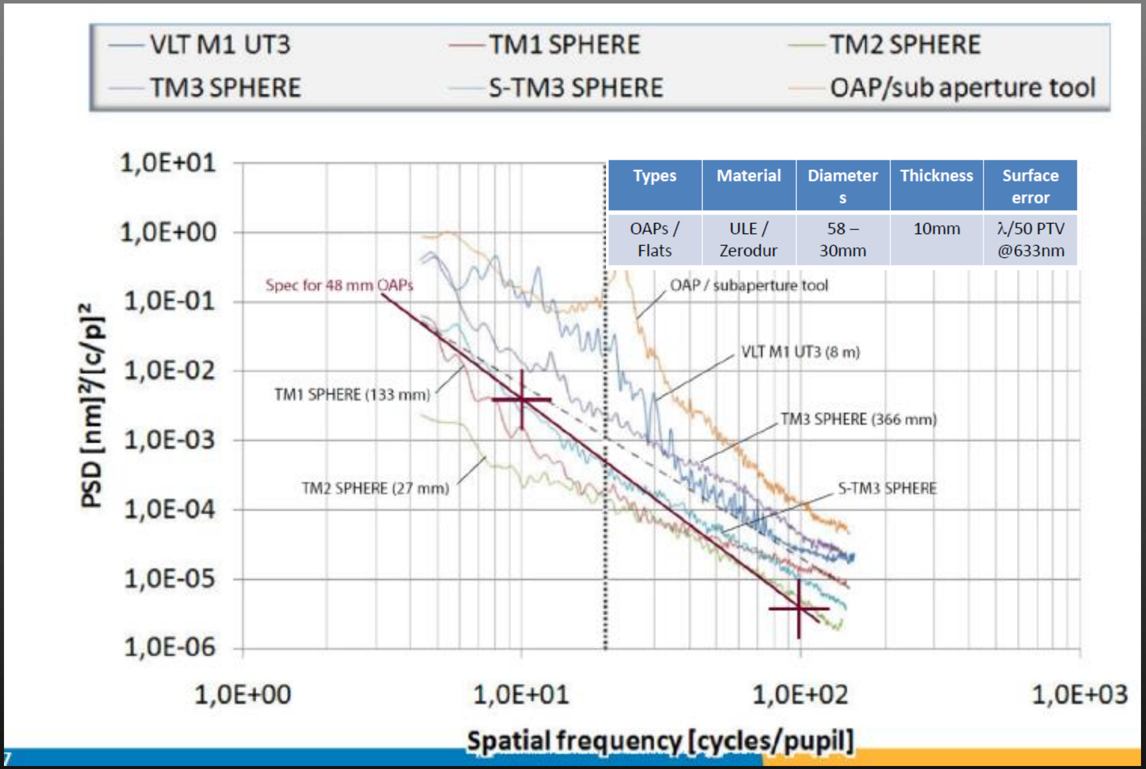
- Large Binocular Telescope Interferometer result – most nearby sunlike stars are not very dusty

WFIRST CGI – Actively Controlled Optical Imaging Instrument With Coronagraph Masks



Optics following the Deformable Mirror are Critcal

- High precision off-axis parabolas to be provided by LAM using stress polishing techniques
- Critical since post deformable mirror; need to maintain wavefront error accuracy

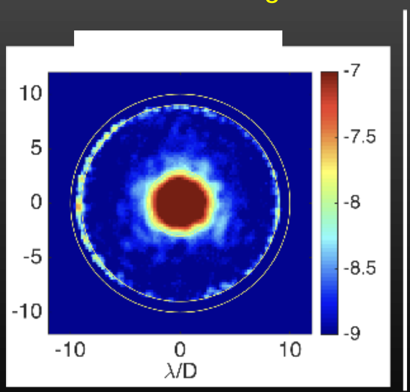


Coronagraph Instrument Operating Modes

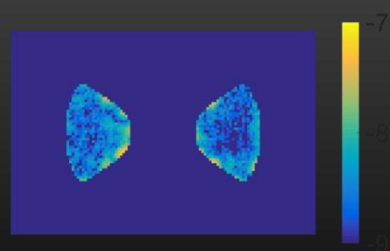
➢ Three Required Technology Demonstration Modes:

Name	λ_{center} (nm)	Spectral Band-width	Channel	Mask Type	Working Angle	Starlight Suppression Region	Can use w/ linear polarizers?
Imaging w/ Narrow FoV	575	10%	Imager	Hybrid Lyot	3-9 λ/D	360°	Y
Spectroscopy	760	18%	Spectrograph	Shaped Pupil	3-9 λ/D	130°	N
Imaging w/ Wide FoV	825	10%	Imager	Shaped Pupil	6.5-20 λ/D	360°	Y

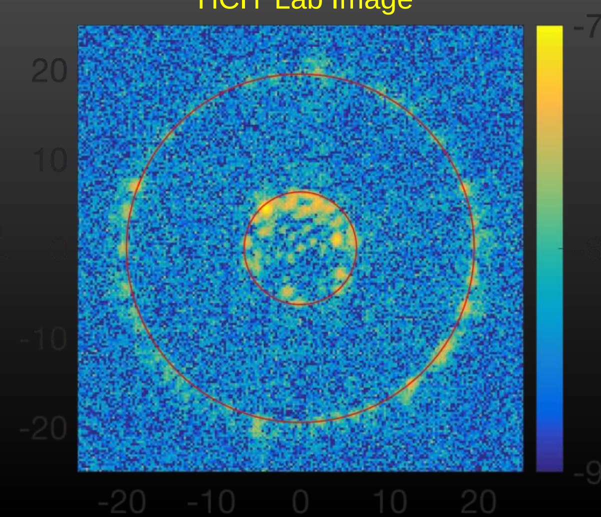
Imaging w/ Narrow FoV
HCIT Lab Image



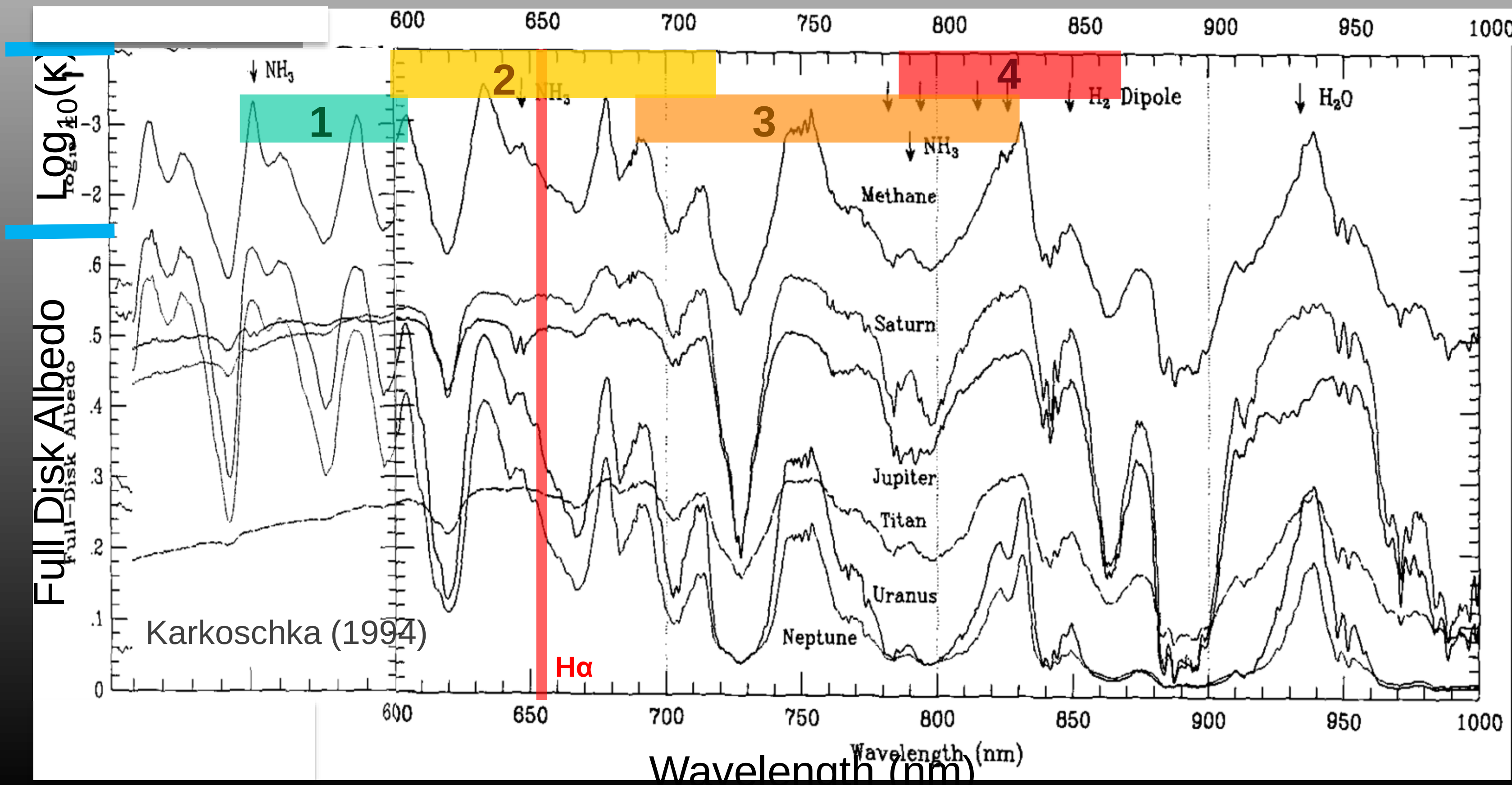
Spectroscopy
HCIT Lab Image



Imaging w/ Wide FoV
HCIT Lab Image

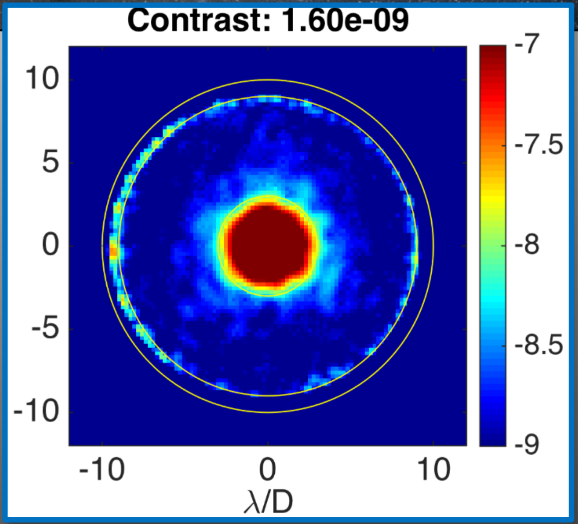


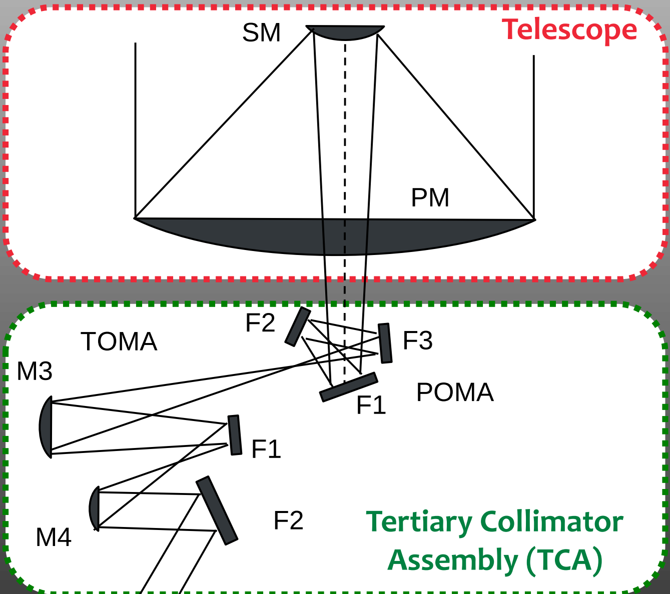
Coronagraph Instrument Filters Span 550-850 nm

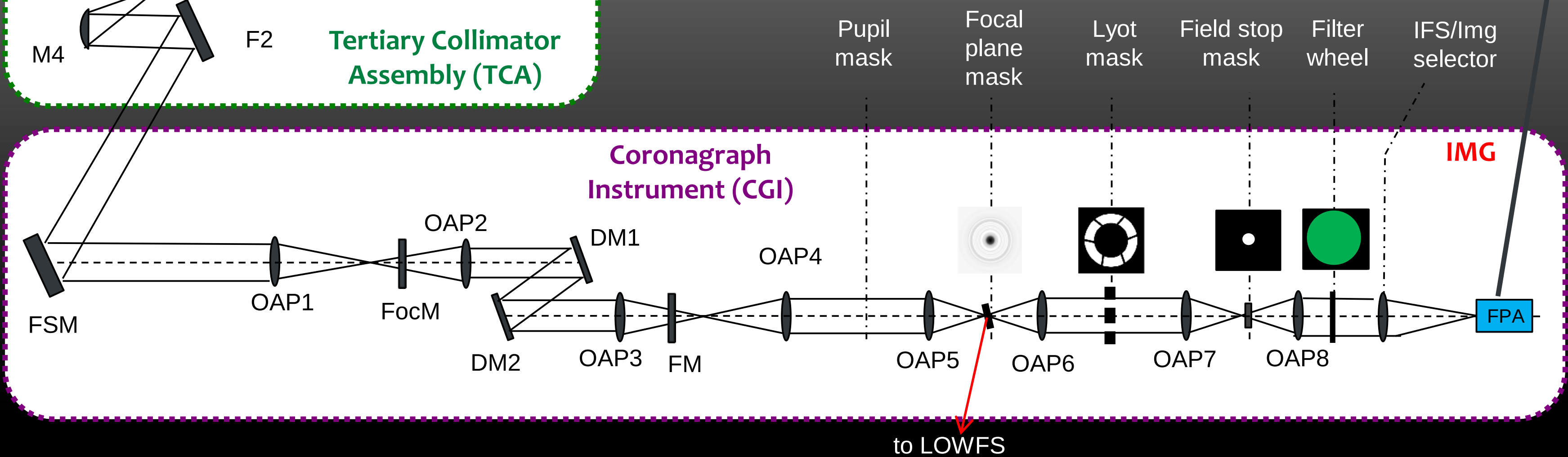


Imaging with Narrow Field of View Mode

Dark hole for planet photometry and discovery centered at 575 nm with annular FOV from 3-9 λ/D

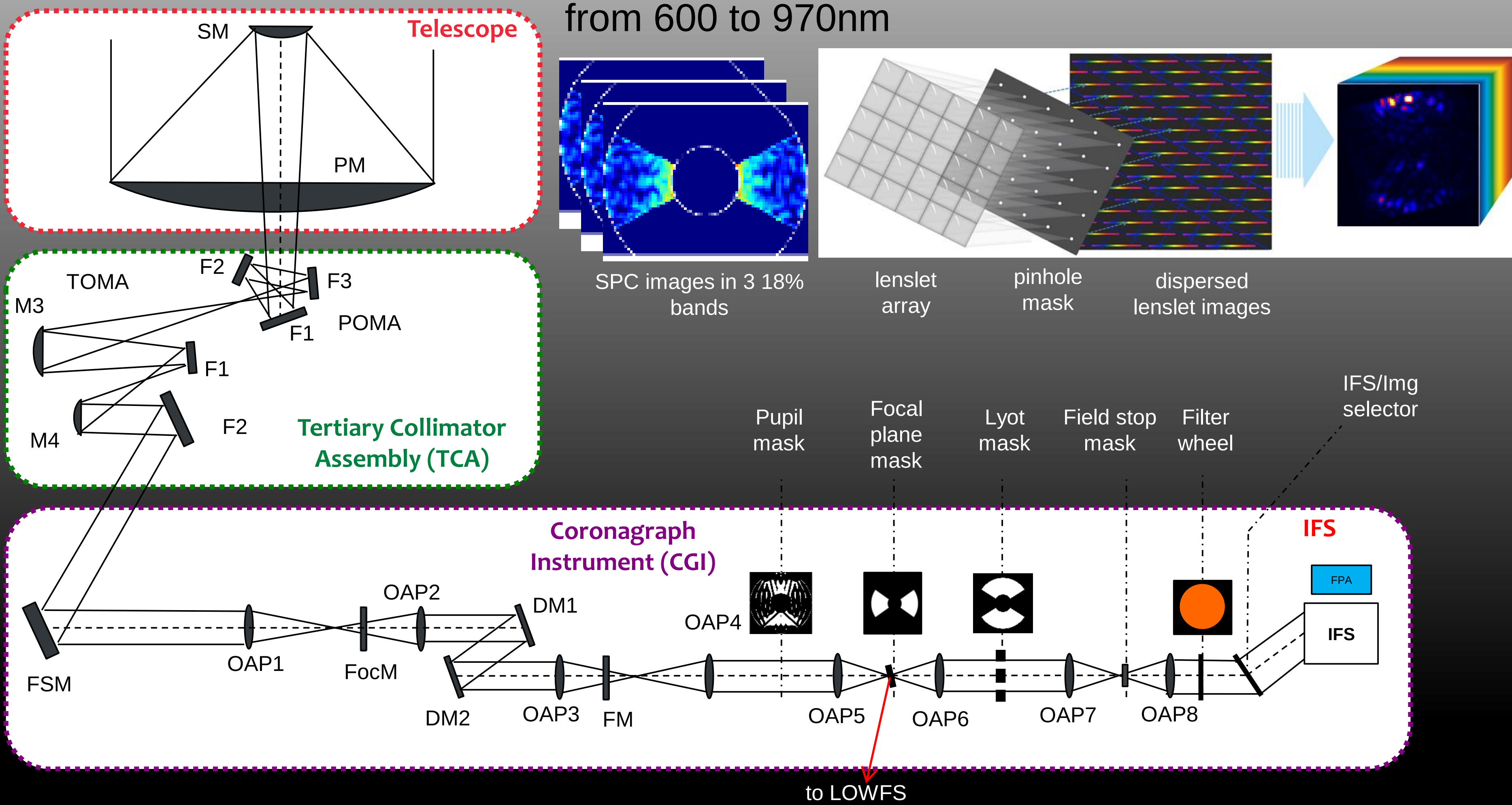




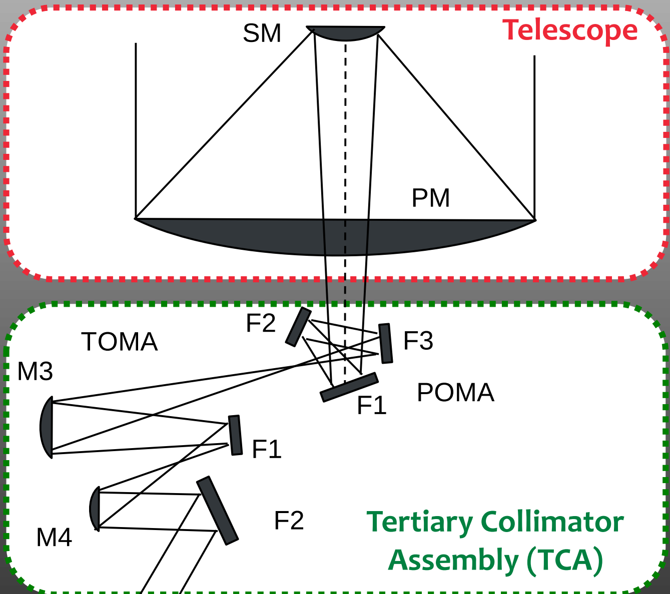


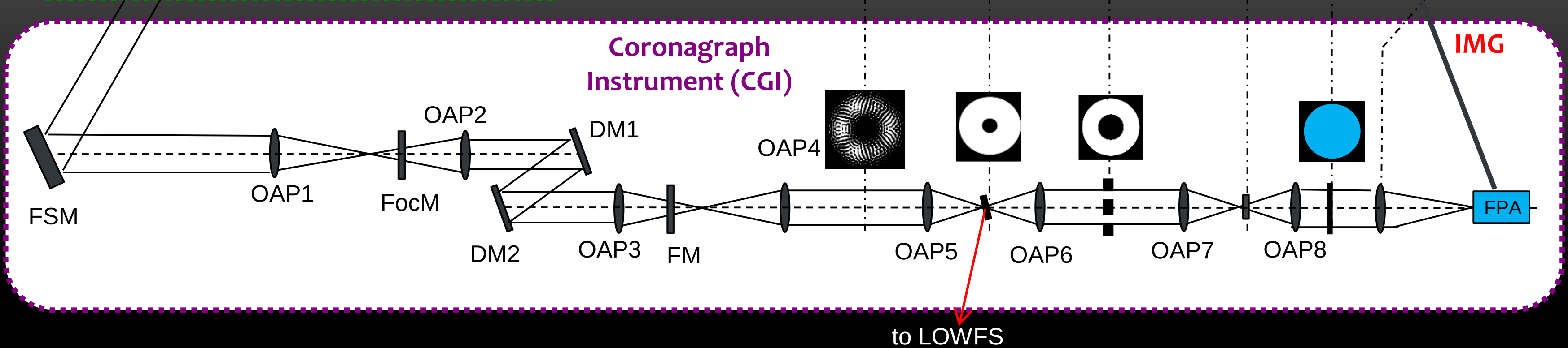
Spectroscopy Mode with Integral Field Spectrograph (IFS)

The IFS uses 3 18% bands to produce R=50 spectra from 600 to 970nm



Imaging with Wide Field of View Mode





Disk imaging at wavelengths 508 and 721 nm, with outer working angle of 20 λ/D

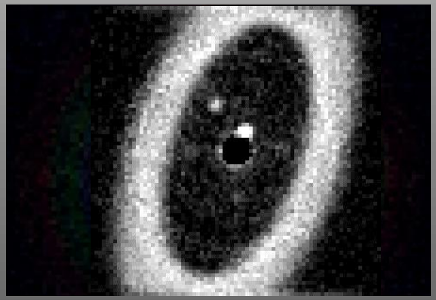
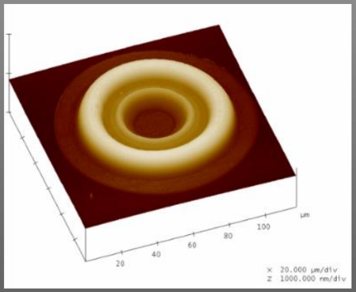


Image from 2015 Exo-C STDT Final Report

Successful Technology Maturation for Coronagraph Instrument

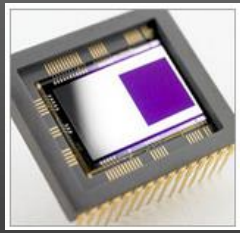
- Pupil plane and focal plane masks for starlight suppression
  - Hybrid Lyot Coronagraph (HLC)
  - Shaped Pupil Coronagraph (SPC)
- Photon-counting electron-multiplying (EM) CCD for detection of very faint planets
  - Teledyne e2v
  - 1K×1K pixels
  - Radiation characterization
- Deformable mirrors for telescope surface error and drift correction
  - Northrop Grumman Xinetics
  - 48×48 actuators
  - Electrostrictive PMN (lead magnesium niobate)
  - Still requires environmental test of interconnect
- Coronagraph system-level performance demonstrated using a testbed with flight-like observatory disturbances:
  - Optical telescope simulator, with simulated pointing and thermal drift errors
  - High-order wavefront sensing and control to system to measure/correct telescope errors
  - Low-order wavefront sensing and control system to measure/correct telescope drift and provide tip/tilt error signal

HLC mask image with an atomic force microscope

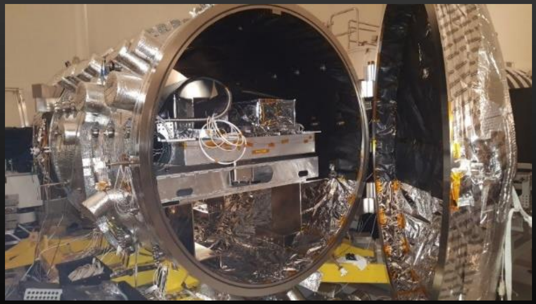


SPC mask image with an atomic force microscope

Xinetics 48 x 48 DM used in JPL's HCIT



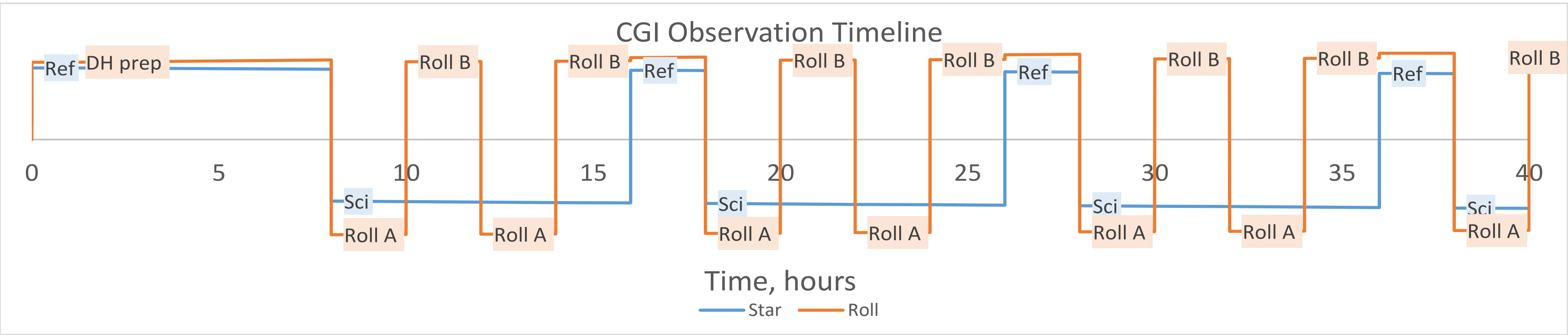
E2V EMCCD used in photon-counting mode

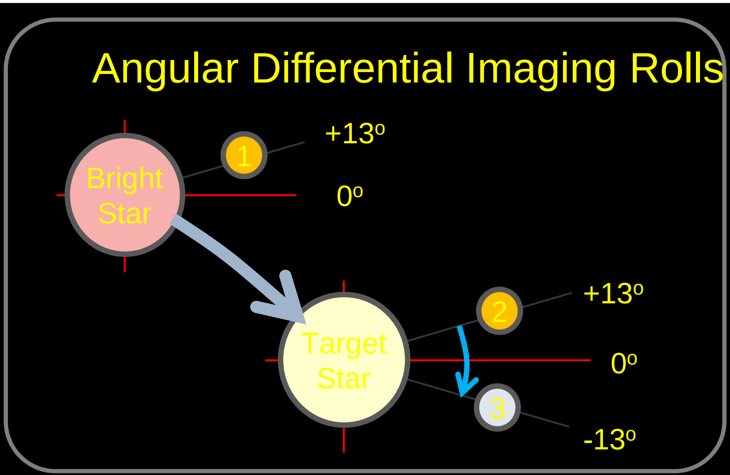


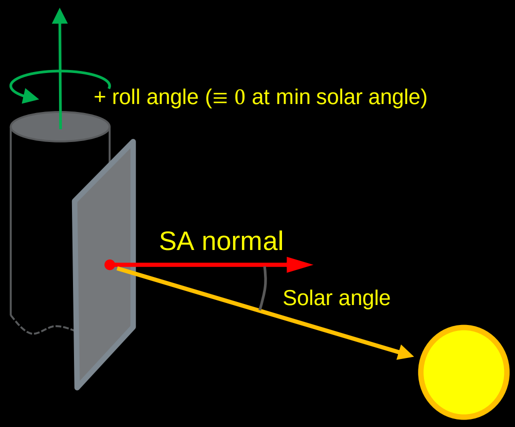
JPL's High Contrast Testbed

Observation: Integration and Chop Cycle

- **Break up long observations (e.g. spectroscopy) by “chopping” between reference and target stars (RDI) and different telescope rolls (ADI) to relax observatory and CGI stability requirements**
- ~20% of observing time on reference, ~10% on slew / roll overheads
- Bright reference star for each target w/ similar solar angle for thermal stability

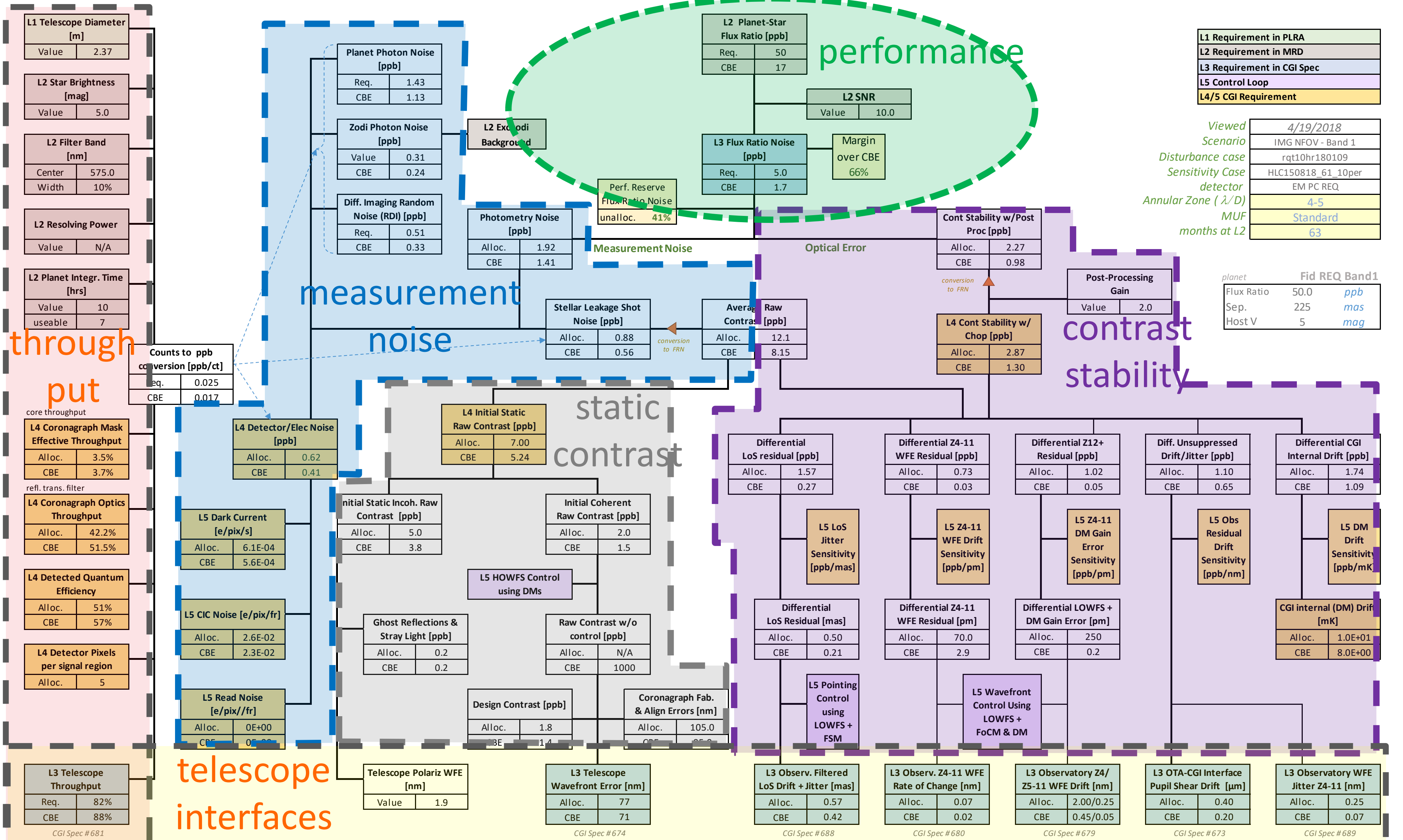






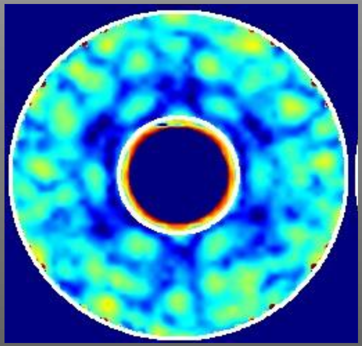
WFIRST

CGI TOP LEVEL ERROR BUDGET | 575 nm 10% BW | IMG NFOV - Band 1 | Revision Date 4/19/2018



CGI Predicted Performance: Initial Raw Contrast

- **Instrument contrast (starlight suppression)** defined in 3 annular rings, for different angular separations from the star
  - Required contrast levels have been demonstrated in the testbed with WFIRST Phase A pupil, HLC in particular has far outperformed required contrast

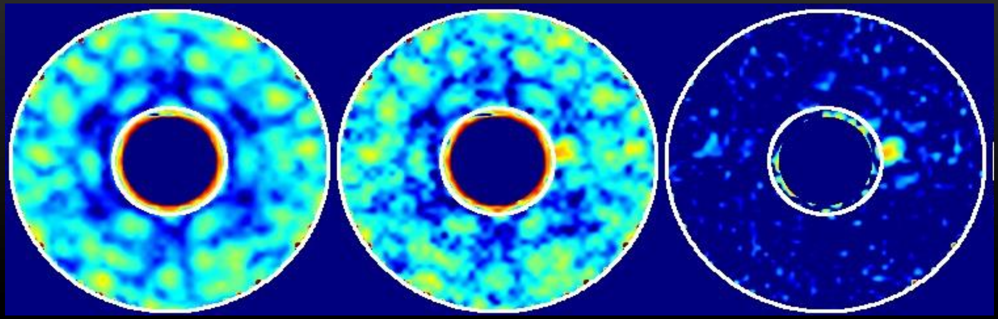


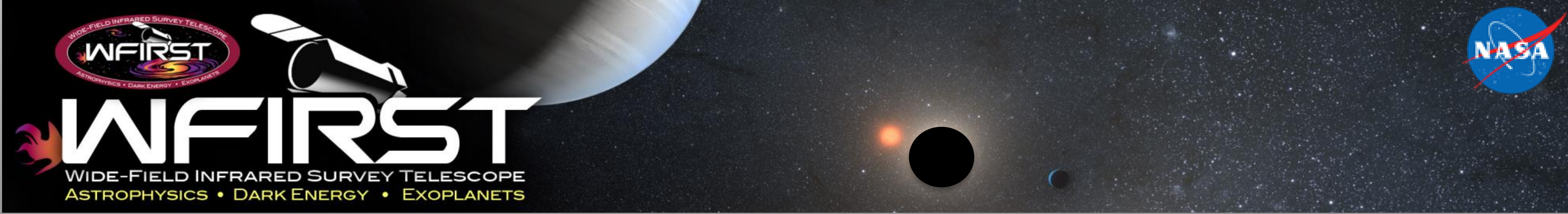
Mode	Current Best Estimate (CBE)	CBE Basis
Imaging with Narrow FoV Raw Contrast	3.8×10^{-9}, 3–4 λ/D 2.5×10^{-9}, 4–8 λ/D 3.8×10^{-9}, 8–9 λ/D	Raw Contrast Error Budget, Validated Against Testbed
Spectroscopy Raw Contrast	1.2×10^{-8}, 3–4 λ/D 8.2×10^{-9}, 4–8 λ/D 1.2×10^{-8}, 8–9 λ/D	Raw Contrast Error Budget, Validated Against Testbed
Imaging with Wide FoV Raw Contrast	3.8×10^{-9}, 6.5–7.5 λ/D 2.5×10^{-9}, 7.5–19 λ/D 3.8×10^{-9}, 19–20 λ/D	Raw Contrast Error Budget, Validated Against Testbed

CGI Predicted Performance: Contrast Stability

- **Instrument contrast (speckle) stability** enables subtraction of residual starlight to see the planet.

Requirement	Current Best Estimate	CBE Basis
Imaging with Narrow FoV Contrast Stability	3.5×10^{-9}, 3–4 λ/D 2.4×10^{-9}, 4–8 λ/D 3.5×10^{-9}, 8–9 λ/D	CGI performance budget
Spectroscopy Contrast Stability	1.2×10^{-9}, 3–4 λ/D 0.8×10^{-9}, 4–8 λ/D 1.2×10^{-9}, 8–9 λ/D	CGI performance budget
Imaging with Wide FoV Contrast Stability	0.6×10^{-9}, 6.5–7.5 λ/D 0.4×10^{-9}, 7.5–19 λ/D 0.8×10^{-9}, 19–20 λ/D	CGI performance budget





Thank you for your attention